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Chapter 5

Bearing Materials

Symbols

$\bar{a}$	linear thermal expansion coefficient, m/mK	$\hat{Q}$	quantity of heat, J
C_p	specific heat, J/(kgK)	Δt_m	temperature change, K
d_b	bore diameter, mm	V	surface velocity, m/s
E	modulus of elasticity, N/m^2	ϵ_1	strain in axial direction
K_f	thermal conductivity, W/mK	ν	Poisson's ratio
m_a	mass, kg	ρ	density, kg/m^3
N_a	rotational speed, rev/min	σ_1	stress in axial direction, N/m^2
P	pressure, N/m^2		

5.1 Introduction

Another factor that can affect the successful operation of tribological elements is the solid materials used. Bearing materials must have special characteristics if the bearings are to operate successfully. Some desirable characteristics that will be explored in this chapter are compatibility with rubbing counterface materials; embeddability for dirt particles and wear debris; conformability to enable the bearing to accommodate misalignment, geometrical errors, and deflection in the structure; thermal stability; corrosion resistance; and fatigue resistance.

5.2 Material Characteristics

The selection of the bearing material for a particular application depends on (1) the type of bearing (journal, thrust, ball, etc.), (2) the type of lubricant (grease, oil, water, gas, etc.), and (3) the environmental conditions (temperature, pressure, etc.). No single material has been developed that can satisfy all

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the requirements of a good bearing material. Therefore, the selection must be made on the basis of the characteristics considered of primary importance in the application.

1. *Compatibility.* Although a properly performing hydrodynamic bearing is one in which the shaft and the bearing are separated by a lubricant film, there are times during the operation when the shaft and the bearing come into contact. High spots on the shaft and the bearing rub, localized heating occurs, the high spots can weld, and the microscopic welds can fracture. This sequence of events results in scoring damage to both the shaft and bearing materials. The ability of these material combinations to resist welding and scoring is a measure of their compatibility.

2. *Embeddability.* In the operation of bearings dirt or other foreign debris is carried into the bearing clearance by the lubricant and by the rotation of the shaft. If this dirt cannot be embedded in the bearing material, scoring damage results. The ability to embed or absorb this dirt determines the embeddability characteristic of the bearing material.

3. *Conformability.* As the term implies, conformability is a measure of the ability of the bearing material to conform to misalignment between the shaft and the bearing or to other geometric inaccuracies produced in manufacturing the parts. Usually, bearing materials having a low modulus of elasticity (low E) are readily conformable.

4. *Corrosion resistance.* The bearing material should be resistant to attack by the lubricant or any of the oxidation products produced during lubricant degradation. For example, lubricating oils without oxidation inhibitors produce organic acids, which attack and corrode certain bearing materials. The selection of materials for use with water as the lubricant is of necessity limited to corrosion-resistant materials.

5. *Fatigue resistance.* High fatigue resistance is necessary in applications in which the load changes direction or in which the load intensity varies cyclically. Fatigue failures appear initially as cracks in the bearing surface. These cracks propagate throughout the bearing material, interconnecting with other cracks and resulting in loose pieces of bearing material. Fatigue strength is particularly important where cyclic loading is present.

6. *Dimensional and thermal stability.* The thermal characteristics of the bearing material are important with regard to both heat dissipation and thermal distortion. The thermal conductivity K_f of the bearing material should be high to ensure maximum dissipation of the frictional heat generated if hydrodynamic lubrication conditions cannot be maintained. The linear thermal expansion coefficient $\bar{\alpha}$ should be acceptable within the overall design so that the effects of temperature variation are not detrimental. Values of K_f and $\bar{\alpha}$ are given in Sec. 5.7. Even if a material has

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these desirable characteristics, additional constraints of acceptable cost and material availability need to be satisfied.

The properties and characteristics of several bearing materials are shown in Table 5.1. Brinell hardness number, load-carrying capacity, and maximum operating temperature are given. Also in this table ratings of fatigue strength, antiseizure property, conformability, and embeddability are given based on an arbitrary scale, with 1 being the most desirable or best.

5.3 Metallics

Bearing materials for conformal surfaces fall into two major categories:

1. *Metallics:* babbitts, bronzes, aluminum alloys, porous metals, and metal overlays such as silver, babbitts, and indium
2. *Nonmetallics:* plastics, rubber, carbon-graphite, wood, ceramics, cemented carbides, metal oxides (e.g., aluminum oxide), and glass

The principal metallic materials will now be covered in more detail.

5.3.1 Tin- and Lead-Base Alloys

The babbitts are among the most widely used materials for hydrodynamically lubricated bearings. Babbitts are either tin or lead-base alloys having excellent embeddability and conformability characteristics. They are unsurpassed in compatibility and thus prevent shaft scoring.

Tin- and lead-base babbitts have relatively low load-carrying capacity. This capacity is increased by metallurgically bonding these alloys to stronger backing materials such as steel, cast iron, or bronze. Babbitt linings are either still cast or centrifugally cast onto the backing material. Fatigue strength is increased by decreasing the thickness of the babbitt lining. Dowson (1998) points out that at the beginning of the century babbitt linings were rarely less than 3 mm thick and not infrequently at least 6.4 mm thick. The need to provide adequate compressive and fatigue strength gradually brought the thickness of the lining down to 500 μm, at the expense of other desirable features such as embeddability and conformability. The optimum thickness of the bearing layer varies with the application but is generally between 0.02 and 0.12 mm.

Tables 5.2 and 5.3 show the composition and physical properties of some of the tin- and lead-base alloys presently used. Table 5.2 shows the significant effect of temperature in decreasing the strength properties of these alloys. The alloys in more general use are shown in Table 5.3. The effect of various percentages of the alloying elements on the mechanical and physical properties of tin- and lead-base alloys can be significant. Increasing the copper or the antimony increases the hardness and the tensile strength and decreases the ductility. However, increases beyond the percentages shown in Table 5.3 can result in decreased fatigue strength.

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Table 5.1: Properties and characteristics of various conformal bearing metals [From Clauser (1948)]

Bearing metal	Brinell hardness number		Load-carrying capacity		Maximum operating temperature		Fatigue strength[a]	Antiseizure property[a]	Conformability and embeddability [a]
	Room temperature	149°C (300°F)	MPa	psi	°C	°F			
Tin-base babbitt	20-30	6-12	5.5-10.4	800-1500	149	300	3	1	1
Lead-base babbitt	15-20	6-12	5.5-8.3	800-1200	149	300	3	1	1
Alkali-hardened lead	22-26	11-17	8.3-10.4	1200-1500	260	500	3	1	1
Cadmium base	30-40	15	10.4-13.8	1500-2000	260	500	3	1	1
Copper lead	20-30	20-23	10.4-17.2	1500-2500	177	350	2	2	2
Tin bronze	60-80	60-70	> 27.6	> 4000	260+	500+	1	3	3
Lead bronze	40-70	40-60	20.7-31.1	3000-4500	232-260	450-500	1	3	3
Phosphor bronze	75-100	65-100	>27.6	> 4000	260+	500+	1	3	3
Aluminum alloy	45-50	40-45	>27.6	> 4000	107-149	225-300	2	2	3
Silver (overplated)	25	25	>27.6	> 4000	260+	500+	1	2	3
Copper-nickel matrix	10	7	13.8	2000	177	350	2	1	2
Trimetal and plated	b	b	>27.6	> 4000	107-149	225-300	2	1	2
Grid type	b	b	>27.6	> 4000	107-149	225-300	2	1	2
Thin babbitt overlay, 0.051-0.178 mm (0.002-0.007 in.	b	b	13.8	2000	149	300	2	1	2
Conventional babbitt overlays, 0.51 mm (0.0020 in.)	b	b	10.4	1500	149	300	2	1	2

[a]This is an arbitrary scale with 1 being the highest rating.
[b]Approximately the same as the babbitts.

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Table 5.2: Composition and physical properties of white metal bearing alloys[a] [From ASTM B23-83. Reprinted by permission of the American Society for Testing and Materials.]

Alloy number[b]	Tin	Antimony	Lead	Copper	Arsenic	Specific gravity[c]	Tin	Antimony	Lead	Copper	20°C (68°F)		100°C (212°F)	
	Specified nominal composition of alloys, percent						Composition of alloys tested, percent				Yield point[d]			
											MPa	psi	MPa	psi
1	91.0	4.5	—	4.5	—	7.34	90.9	4.52	None	4.56	30.3	4400	18.3	2650
2	89.0	7.5	—	3.5	—	7.39	89.2	7.4	0.03	3.1	42.0	6100	20.6	3000
3	84.0	8.0	—	8.0	—	7.46	83.4	8.2	.03	8.3	45.5	6600	21.7	3150
7	10.0	15.0	Remainder	—	.45	9.73	10.0	14.5	75.0	.11	24.5	3550	11.0	1600
8	5.0	15.0	Remainder	—	.45	10.04	5.2	14.9	79.4	.14	23.4	3400	12.1	1750
15	1.0	16.0	Remainder	—	1.0	10.05	—	—	—	—	—	—	—	—

Alloy number[b]	20°C (68°F)		100°C (212°F)		20°C (68°F)		100°C (212°F)		20°C (68°F)	100 °C (212°F)	Melting point		Temperature of complete liquefaction		Proper pouring temperature	
	Johnson's apparent elastic limit[e]				Ultimate strength in compression[f]				Brinell harness[g]							
	MPa	psi	MPa	psi	MPa	psi	MPa	psi	MPa	psi	°C	°F	°C	°F	°C	°F
1	16.9	2450	7.2	1050	88.6	12,850	47.9	6950	8.0	17.0	223	433	371	700	441	825
2	23.1	3350	7.6	1100	102.7	14,900	60.0	8700	12.0	24.5	241	466	354	669	424	795
3	36.9	5350	9.0	1300	121.3	17,600	68.3	9900	14.5	27.0	240	464	422	792	491	915
7	17.2	2500	9.3	1350	107.9	15,650	42.4	6150	10.5	22.5	240	464	268	514	338	620
8	18.3	2650	8.3	1200	107.6	15,600	42.4	6150	9.5	20.0	237	459	272	522	341	645
15	—	—	—	—	—	—	—	—	13.0	21.0	248	479	281	538	350	662

[a]Compression test specimens were cylinders 1.5 in. (38 mm) in length and 0.5 in. (13 mm) in diameter, machined from chill castings 2 in. (51 mm) in length and 0.75 in (19 mm) in diameter. The Brinell tests were made on the bottom of parallel machined specimens cast in a mold 2 in. (51 mm) in diameter and 0.0625 in. (16 mm) deep at room temperature

[b]Data not available on alloys 11 and 13.

[c]The specific gravity multiplied by 0.0361 equals the mass density in pounds per cubic inch.

[d]The values for yield point were taken from stress-strain curves at a deformation of 0.125 percent of gage length.

[e]Johnson's apparent elastic limit is taken as the unit stress at the point where the slope of the tangent to the curve is two-thirds its slope at the origin.

[f]The ultimate strength values were taken as the unit load necessary to produce a deformation of 25 percent of the specimen length.

[g]These values are the average Brinell number of three impressions on each alloy, using a 10-mm (0.39-in) ball and a 500-kg (1102.3 lb) load applied for 30 s.

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Table 5.3: Chemical composition of alloys in more general use. [From ASTM B23-83. Reprinted by permission of the American Society for Testing and Materials.]

Element	Alloy number[a,b]							
	Tin base				Lead base			
	1	2	3	11	7	8	13	15
	Chemical composition, percent							
Tin	90.0-92.0	88.0-90.0	83.0-85.0	86.0-89.0	9.3-10.7	4.5-5.5	5.5-6.5	0.8-1.2
Antimony	4.0-5.0	7.0-8.0	7.5-8.5	6.0-7.5	14.0-16.0	14.0-16.0	9.5-10.5	14.5-17.5
Lead	.35	.35	.35	.50	Remainder[c]	Remainder	Remainder	Remainder
Copper	4.0-5.0	3.0-4.0	7.5-8.5	5.0-6.5	.50	.50	.50	.6
Iron	.08	.08	.08	.08	.10	.10	.10	.10
Arsenic	.10	.10	.10	.10	.30-.60	.30-.60	.25	.8-1.4
Bismuth	.08	.08	.08	.08	.10	.10	.10	.10
Zinc	.005	.005	.005	.005	.005	.005	.005	.005
Aluminum	.005	.005	.005	.005	.005	.005	.005	.005
Cadmium	.05	.05	.05	.05	.05	.05	.05	.05
Total named elements, minimum	99.80	99.80	99.80	99.80	—	—	—	—

[a] All values not given as ranges are maximum values unless shown otherwise.

[b] Alloy 9 was discontinued in 1946 and 4,5,6,10,11,12,16, and 19 were discontinued in 1959. A new number 11, similar to SAE grade 11, was added in 1966.

[c] To be determined by difference.

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5.3.2 Copper-Lead Alloys

Two alloys, one consisting of 60% copper and 40% lead and the other of 70% copper and 30% lead, or slight variations, are used as lining materials on steel-backed bearings. These alloys are either strip cast or sintered onto the backing strip, thus providing a bearing with a higher load-carrying capacity than one lined with the babbitt alloys. They also have higher fatigue resistance and can operate at higher temperatures, but they have poor antiseizure properties. They are used in automotive and aircraft internal combustion engines and in diesel engines. Their high lead content provides a good bearing surface but makes them susceptible to corrosion. Their corrosion resistance and antiseizure properties are improved when they are used as trimetal bearings with a lead-tin or lead-indium overlay electrodeposited onto the copper-lead surface.

5.3.3 Bronzes

Several bronze alloys, including lead, tin, and aluminum bronzes, are used extensively as bearing materials. Some are described in Table 5.4. Because of their good structural properties, they can be used as cast bearings without a steel backing. Bearings can also be machined from standard bar stock.

Lead bronzes, which contain up to 25% lead, provide higher load-carrying capacity and fatigue resistance and a higher temperature capability than the babbitt alloys. Tin contents up to about 10% are used to improve the strength properties. Higher-lead bronze (70% copper, 5% tin, and 25% lead) can be used with soft shafts, but harder shafts (300 BHN) are recommended with the harder lower-lead bronzes, particularly under conditions of sparse lubrication. Lead bronze bearings are used in pumps, diesel engines, railroad cars, home appliances, and many other applications.

Tin bronzes, which contain 9 to 20% tin and small quantities of lead (usually $< 1\%$), are harder than lead bronzes and are therefore used in heavier-duty applications.

5.4 Nonmetallics

Although nonmetallic materials such as rubber and graphite have found increasing application, polymeric and plastic materials have had the greatest recent impact in triboelements. These materials fall into two categories: thermosetting and thermoplastic materials. In thermosetting materials the fabrics of nonoriented fibers are generally set in phenolic, or occasionally cresylic, resins.

Of the thermoplastic materials nylon has been recognized as a valuable bearing material as has the remarkable low-friction polymer polytetrafluoroethylene (PTFE). The great merit of these materials is that they can operate effectively without lubricants, although their mechanical properties generally limit their application to lightly loaded conditions and often to low speeds and conforming surfaces.

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Table 5.4: Typical bronze and copper alloy bearing materials [From Booser (1966)]

Designation	Material	Nominal composition, percent						Brinell hardness number BNH	Tensile strength		Maximum operating temperature		Maximum load	
		Cu	Sn	Pb	Zn	Fe	Al		MPa	ksi	°C	°F	MPa	ksi
SAE 480	Copper lead	65	—	35	—	—	—	25	55.2	8	177	350	13.8	2
AMS 4840	High-lead tin bronze	70	5	25	—	—	—	48	172.5	25	204+	400+	20.7+	3+
SAE 67	Semiplastic bronze	78	6	16	—	—	—	55	207.0	30	232	450	20.7+	3+
SAE 40	Leaded red brass	85	5	5	5	—	—	60	241.5	35	232	450	24.2	3.5
SAE 660	Bronze	83	7	7	3	—	—	60	241.5	35	232+	450+	27.6	4
SAE 64	Phosphor bronze	80	10	10	—	—	—	63	241.5	35	232+	450+	27.6	4
SAE 62	Gunmetal	88	10	—	2	—	—	65	310.5	45	260+	500+	27.6	4
SAE 620	Navy G	88	8	—	4	—	—	68	276.0	40	260	500	27.6+	4+
SAE 63	Leaded gunmetal	88	10	2	—	—	—	70	276.0	45	260	500	27.6+	4+
ASTM B148-52-9c	Aluminum bronze	85	—	—	—	4	11	195	621.0	90	260+	500+	31.1+	4.5+

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Table 5.5: Limits of application of nonmetallic bearing materials. [*Revised from O'Connor et al. (1968).*]

Material	Load-carrying capacity		Maximum temperature		Maximum speed		PV limit[a]
	MPa	psi	°C	°F	m/s	ft/min	
Carbon graphite	4.1	600	399	750	12.7	2500	15×10^3
Phenolics	41.4	6000	93	200	12.7	2500	15×10^3
Nylon	6.9	1000	93	200	5.1	1000	3×10^3
PTFE (Teflon)	3.4	500	260	500	0.51	100	1×10^3
Reinforced PTFE	17.2	2500	260	500	5.1	1000	10×10^3
PTFE fabric	414.0	60,000	260	500	0.25	50	25×10^3
Polycarbonate (Lexan)	6.9	1000	104	220	5.1	1000	3×10^3
Acetal resin (Delrin)	6.9	1000	82	180	5.1	1000	3×10^3
Rubber	0.34	50	66	150	7.6	1500	15×10^3
Wood	13.8	2000	66	150	10.2	2000	15×10^3

[a] P = load (psi); V = surface speed (ft/min).

The limits of applying nonmetallic materials are shown in Table 5.5. The specific limits shown in this table are load-carrying capacity, maximum temperature, maximum speed, and PV limit, where P is the pressure expressed in pounds force per square inch and V is the surface speed expressed in feet per minute.

5.4.1 Carbon Graphites

In addition to their excellent self-lubricating properties, carbon graphites have several advantages over conventional materials and lubricants. They can withstand temperatures of approximately 370°C in an oxidizing atmosphere such as air and can be used in inert atmospheres to 700°C or at cryogenic temperatures. They can be used in equipment in which lubricant contamination must be prevented, such as textile machinery and food-handling machinery. Carbon graphites are highly resistant to chemical attack and are used in applications where the chemicals attack conventional lubricants. They can be used with low-viscosity lubricants, such as water, gasoline, or air.

Carbon graphites are used for pump shaft bearings, impeller wear rings in centrifugal pumps, and journal and thrust bearings in covered motor pumps and for many other applications. Because of its low expansion coefficient of 2.7×10^{-6} mm/mm·°C, a carbon graphite liner is shrunk-fit into a steel sleeve. The steel backing provides mechanical support, improves heat transfer, and helps to maintain shaft clearance. The mating shaft should be made of harder metals. Chromium plates, hardened tool steels, or even some ceramics are used.

A PV value of 15,000 is used when lubricant is present. Depending on the material grade and the application, friction coefficients ranging from 0.04 to 0.25 are obtainable. Absorbed water vapor enhances film formation and reduces the friction and wear of carbon graphite. With no water vapor present

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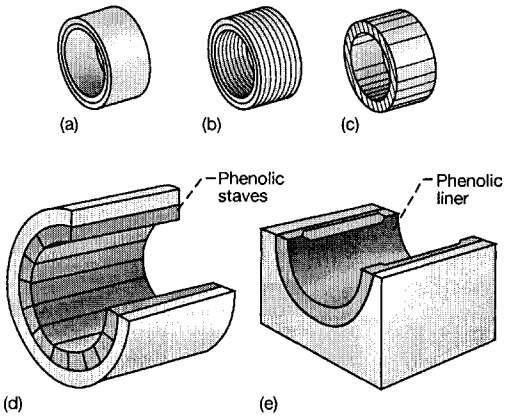

Figure 5.1: Phenolic laminate bearings. (a) Tubular bearing; (b) circumferentially laminated bearing; (c) axially laminated bearing; (d) stave bearing; (e) molded bearing. [*From Kaufman (1980).*]

(low humidity), wear increases. In general, low speeds and light loads should he used in nonlubricated applications.

5.4.2 Phenolics

Among several types of plastic bearings presently in use are the phenolics. These are in the form of laminated phenolics, made by treating sheets of either paper or fabric with phenolic resin, stacking the desired number of sheets, and curing with heat and pressure to bond them together and set the resin. Other filling materials, such as graphite and molybdenum disulfide, are added in powdered form to improve lubrication qualities and strength.

Figure 5.1 shows the various orientations of the phenolic laminates used in bearings. Tubular bearings (Fig. 5.1a) are used where complete bushings are required. Bearings in which the load is taken by the edges of the laminations (Fig. 5.1b and c) are used in light-duty service. Stave bearings (Fig. 5.1d) are used mainly for stern-tube and rudder-stock bearings on ships and for guide bearings on vertical waterwheel turbines. Molded bearings (Fig. 5.1e) are used for roll-neck bearings in steel mills or for ball-mill bearings. Table 5.6 gives some typical applications of phenolic bearings.

Laminated phenolics operate well with steel or bronze journals when lubricated with oil, water, or other liquids. They have good resistance to seizure. One main disadvantage of these materials is their low thermal conductivity (0.35 W/m·°C, about 1/150 that of steel), which prevents them from dissipating frictional heat readily and can result in their failure by charring. In large roll-neck bearings the heat is removed by providing a large water flow through the bearing.

Laminated phenolics have good resistance to chemical attack and can be used with water, oil, diluted acid, and alkali solutions. They have good conformability, having an elastic modulus of 3.45 to 6.90 GPa, in comparison with

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Table 5.6: Typical applications of laminated phenolic bearings [*From Kaufman (1980)*].

Bearing application	Type[a]	Size range		Fabric weight		Resin	Lubricant	Diametral clearance[b]		Principal reasons for using laminated phenolic bearing material
		mm	in.	g/m	oz/yd			mm	in.	
Roll neck	(e)	76-762	3-30	466-1552	15-50	40-60	Water or emulsion	0-13	0-0.5	Longer life, power savings due to lower friction, lower-cost water lubrication, greater cleanliness of operation, better holding of gage due to less water.
Ship, stern tube	(d)	76-660	3-26	248	8	60	Water	0.001/mm diameter over 127 mm	0.001/in. diameter over 5 in.	Longer life, greater ease of handling and installing, higher load-carrying capacity particularly with impact loads, lower
Rudder, pintle	(a), (d)	76-660	3-26	93-248	3-8	55-60	Grease or water	0.001/mm diameter over 127 mm	0.001/in. diameter over 5 in.	friction, greater corrosion and decay resistance, lower journal wear, greater local availability
Small craft, stern tube	(c)	13-76	.5-3	248	8	60	Water	.127	.005	
Centrifugal pump	(a),(b),(c)	13-102	.5-4	93-248	3-8	60	Pumped liquid	.127	.005	Longer life, better lubrication with pumped liquid (water, gasoline, chemical solutions, etc.)
Water wheel, turbine, guide bearing	(d)	102-610	4-24	248	8	60	Water	.127	.005	Longer life, lower friction, no decay, less journal wear
Ball mill	(a),(e)	381-1219	15-49	202-466	6.5-15	55-60	Water or emulsion of water and grease	.381-.762	.015-0.30	Longer life, higher load-carrying capacity, lower friction, lower lubricant cost
Aircraft, landing gear	(a)	51-381	2-12	93	3	60	Oil	0.001/mm diameter over 127 mm	0.001/in. diameter over 5 in.	Lighter weight, satisfactory dimensional stability and load-carrying capacity
Railway, bolster cup	Molded cone	—	—	202	6.5	53	Grease	—	—	Longer life, lower noise and vibration transmission

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about 3.45 GPa for babbitts. Laminated phenolics also have a high degree of embeddability. This property is advantageous in ship stern-tube bearings, which are lubricated by water that contains sand and other sediment. Because of their good resilience, they are highly resistant to damage by fatigue and shock loading. They do not hammer out or extrude under shock loading as do some babbitt alloys. Because laminated phenolics are made up of organic fibers that absorb certain liquids and expand, small changes in dimensions can occur. Water or lubricants containing water have a greater measurable effect on the dimensional stability of phenolics than do oils. Expansion is greater perpendicular to the laminations (2 to 3%) than parallel (0 to 0.3 percent).

5.4.3 Nylon

Nylon is one of the classes of thermoplastic materials, as differentiated from the thermosetting plastics, the phenolics. Nylon bearings can be molded, or nylon powders can be sintered in a manner similar to the manufacture of porous metals. Nylon is not affected by petroleum oils and greases, food acids, milk, photographic solutions, etc., and thus can be used in applications where these fluids are handled.

Nylon has good abrasion resistance, a low wear rate, and good embeddability. Like most plastics, it has good antiseizure properties and softens or chars rather than seizing. It has low thermal conductivity (0.24 W/m·°C), and failure is usually the result of overheating. Cold flow (creep) under load is one of its main disadvantages. This effect can be minimized by supporting thin nylon liners in metal sleeves. Nylon bearings are used in household applications such as mixers and blenders and for other lightly loaded applications.

5.4.4 Teflon

Teflon is a thermoplastic material based on the polymer polytetrafluoroethylene (PTFE), which has a low friction coefficient. It has excellent self-lubricating properties and in many applications can be used dry. It is resistant to chemical attack by many solvents and chemicals and can be used in the temperature range -260 to 260°C. Like nylon, it has a tendency to cold-form under loads. Teflon in its unmodified form also has the disadvantages of low stiffness, a high thermal expansion coefficient, low thermal conductivity, and poor wear resistance. These poor properties are greatly improved by adding fibers such as glass, ceramics, metal powders, metal oxides, graphite, or molybdenum disulfide.

5.5 Form of Bearing Surfaces

The metallic and nonmetallic materials described in the two preceding sections may be applied to bearing surfaces in several ways, (as shown in Fig. 5.2):

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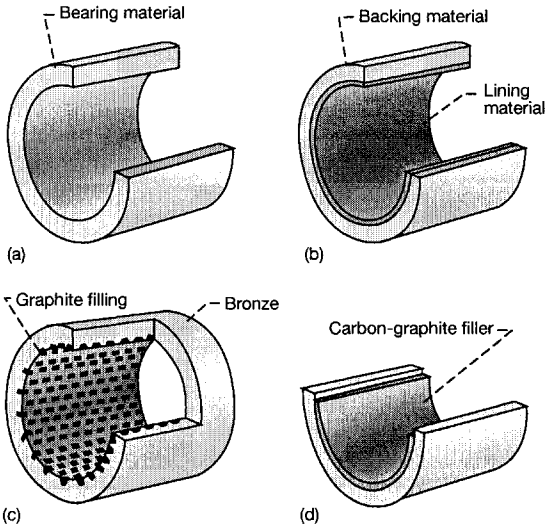

Figure 5.2: Different forms of bearing surfaces. (a) Solid bearing; (b) lined bearing; (c) filled bearing; (d) shrink-fit bearing.

- Solid bearing (Fig. 5.2a). Bearings are machined directly from a single material (cast iron, aluminum alloys, bronzes, porous metals, etc.).
- Lined bearing (Fig. 5.2b). Bearing material is bonded to a stronger backing material. The thickness of the bearing lining may range from 0.25 mm to as much as 13 mm. Most modern bonding techniques are metallurgical, although chemical and mechanical methods are also used. The lining material may be cast, sprayed, electrodeposited, or chemically applied.
- Filled bearing (Fig. 5.2c). A stronger bearing material is impregnated with a bearing material that has better lubricating properties (e.g., graphite impregnated into a bronze backing).
- Shrink-fit liner bearing Fig. 5.2d). Carbon-graphite or plastic liners are shrunk into a metal hacking sleeve by retaining devices such as setscrews, dowels, and clamping flanges.

5.6 Materials and Manufacturing Processes Used for Rolling-Element Bearings

Nonconformal surfaces such as rolling-element bearings operate under conditions that impose high compressive stresses for millions of stress cycles as the

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balls or the rollers rotate through the loaded zone of the bearing. For such applications the race and ball materials should be hard and have high fatigue resistance.

Until about 1955 the technology of rolling-element bearing materials did not receive much attention from materials scientists. Bearing materials were restricted to SAE 52100 and some carburizing grades such as AISI 4320 and AISI 9310, which seemed to be adequate for most bearing applications, despite the limitation in temperature of about 176°C for 52100 steel. A minimum acceptable hardness of Rockwell C 58 was specified. Experiments indicated that fatigue life increased with increasing hardness.

The advent of the aircraft gas turbine engine, with its need for advanced rolling-element bearings, provided the major impetus for advancements in the technology of rolling-element bearing materials. Higher temperatures, higher speeds and loads, and the need for greater durability and reliability all served as incentives for developing and evaluating a broad range of new materials and processing methods. The combined research efforts of bearing manufacturers, engine manufacturers, and government agencies over the past three decades have resulted in startling advances in rolling-element bearing life, reliability, and performance. The discussion here is narrow in scope. For a comprehensive treatment of the research status of current bearing technology and current bearing designs, refer to Bamberger et al. (1980).

5.6.1 Ferrous Alloys

The need for higher temperature capability led to the evaluation of several available molybdenum and tungsten alloy tool steels as bearing materials. These alloys have excellent high-temperature hardness retention. Such alloys melted and cast in an air environment were, however, generally deficient in fatigue resistance because of nonmetallic inclusions. Vacuum processing techniques can reduce or eliminate these inclusions. Techniques used include vacuum induction melting (VIM) and vacuum arc remelting (VAR). These have been extensively explored, not only with the tool steels now used as bearing materials but with SAE 52100 and some of the carburizing steels as well. Table 5.7 lists a fairly complete array of ferrous alloys, both fully developed and experimental, from which present-day bearings are fabricated. AISI M-50, usually VIM-VAR or consumable electrode vacuum melted (CEVM), has become a widely used quality bearing material. It is usable at temperatures to 315°C, and it is usually assigned a materials life factor of 3 to 5. T-1 tool steel has also come into fairly wide use in bearings, mostly in Europe. Its hot hardness retention is slightly superior to that of M-50 and approximately equal to that of M-1 and M-2. These alloys retain adequate hardness to about 400°C.

Surface-hardened or carburized steels are used in many bearings where, because of shock loads or cyclic bending stresses, the fracture toughness of through-hardened steels is inadequate. Some of the newer materials being developed, such as CBS 1000 and Vasco X-2, have hot hardness retention compa-

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Table 5.7: Typical compositions of selected bearing steels [From Bamberger et al. (1980)]

Designation	C	P (max)	S (max)	Mn	Si	Cr	V	W	Mo	Co	Cb	Ni
	Alloying element, wt %											
SAE 52100[a]	1.00	0.025	0.025	0.35	0.30	1.45	—	—	—	—	—	—
MHT[b]	1.03	0.025	0.025	0.35	0.35	1.50	—	—	—	—	—	—
AISI M-1	0.80	0.030	0.030	0.30	0.30	4.00	1.00	1.50	8.00	—	—	—
AISI M-2[a]	0.83	0.030	0.030	0.30	0.30	3.85	1.90	6.15	5.00	—	—	—
AISI M-10	0.85	0.030	0.030	0.25	0.30	4.00	2.00	—	8.00	—	—	—
AISI M-50[a]	0.80	0.030	0.030	0.30	0.25	4.00	1.00	—	4.25	—	—	—
T-1 (18-4-1)[a]	0.70	0.030	0.030	0.30	0.25	4.00	1.00	18.0	—	—	—	—
T15	1.52	0.010	0.004	0.26	0.25	4.70	4.90	12.5	0.20	5.10	—	—
440C[a]	1.03	0.018	0.014	0.48	0.41	17.30	0.14	—	0.50	—	—	—
AMS 5749	1.15	0.012	0.004	0.50	0.30	14.50	1.20	—	4.00	—	—	—
Vasco Matrix II	0.53	0.014	0.013	0.12	0.21	4.13	1.08	1.40	4.80	7.81	—	0.10
CRB-7	1.10	0.016	0.003	0.43	0.31	14.00	1.03	—	2.02	—	0.32	—
AISI 9310[c]	0.10	0.006	0.001	0.54	0.28	1.18	—	—	0.11	—	—	3.15
CBS 600[c]	0.19	0.007	0.014	0.61	1.05	1.50	—	—	0.94	—	—	0.18
CBS 1000M[c]	0.14	0.018	0.019	0.48	0.43	1.12	—	—	4.77	—	—	2.94
Vasco X-2[c]	0.14	0.011	0.011	0.24	0.94	4.76	0.45	1.40	1.40	0.03	—	0.10

[a] Balance, iron.
[b] Also contains 1.36% Al.
[c] Carburizing grades.

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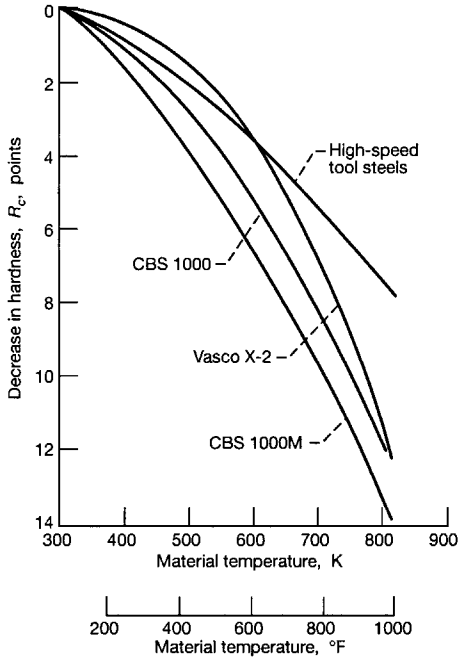

Figure 5.3: Hot hardness of CBS 1000, CBS 1000M, Vasco X-2, and high-speed tool steels. [*From Anderson and Zaretsky (1975).*]

rable to that of the tool steels (Fig. 5.3). They too are available as ultraclean, vacuum-processed materials and should offer adequate resistance to fatigue. Carburized steels may become of increasing importance in ultra-high-speed applications. Bearings with through-hardened steel races are currently limited to approximately 2.5 million $d_b N_a$ (where d_b is bore diameter in millimeters and N_a is rotational speed in revolutions per minute). At higher $d_b N_a$ values fatigue cracks propagate through the rotating race as a result of excessive hoop stress (Bamberger et al., 1976).

In applications where the bearings are not lubricated with conventional oils and protected from corrosion at all times, a corrosion-resistant alloy should be used. Dry-film-lubricated bearings, bearings cooled by liquefied cryogenic gases, and bearings exposed to corrosive environments such as high humidity and salt water are applications where corrosion-resistant alloys should be considered. Of the alloys listed in Table 5.7, both 440C and AMS 5749 are readily available in vacuum-melted heats.

Forging and forming methods that result in improved resistance to fatigue have also been developed. Experiments indicate that fiber or grain flow parallel to the stressed surface is superior to fiber flow that intersects the stressed surface (Bamberger, 1970; Zaretsky and Anderson, 1966). Forming methods that result in more parallel grain flow are now being used in the manufacture of many bearings, especially those for high-load applications.

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5.6.2 Ceramics

Experimental bearings have been made from a variety of ceramics including alumina, silicon carbide, titanium carbide, and silicon nitride. The use of ceramics as bearing materials for specialized applications will probably continue to grow for several reasons. These include

- High-temperature capability. Because ceramics can exhibit elastic behavior to temperatures beyond 1000°C, they are an obvious choice for extreme temperature applications.
- Corrosion resistance. Ceramics are essentially chemically inert and able to function in many environments hostile to ferrous alloys.
- Low density. This can be translated into improved bearing capacity at high speeds, where centrifugal effects predominate.
- Low thermal expansion coefficient. Under severe thermal gradients, ceramic bearings exhibit less drastic changes in geometry and internal play than do ferrous alloy bearings.

Silicon nitride has been developed as a bearing material (Sibley, 1982; Cundill and Giordano, 1982). Silicon nitride bearings have exhibited fatigue lives comparable to and in some instances superior to that of high-quality vacuum-melted M-50 (Sibley, 1982). Two problems remain: (1) quality control and precise nondestructive inspection techniques to determine acceptability and (2) cost. Improved hot isostatic compaction, metrology, and finishing techniques are all being actively pursued.

5.7 Properties of Common Bearing Materials

This section provides representative values for a number of solid material properties required in evaluating fluid film bearings. The tables and figures presented in this section came from ESDU (1984). With many materials a wide range of property values is attainable by, for example, heat treatment or a small change in composition. The quoted values given in the tables are therefore only typical values likely to be met in fluid film lubrication applications. Unless otherwise stated, all material properties are quoted for room temperature (20°C).

Bearing materials have been conveniently grouped into three basic classifications: metals, ceramics, and polymers. This scheme is based primarily on chemical makeup and atomic structure, and most materials fall into one distinct grouping or another, although there are some intermediates. In addition to these three major classifications, there is one additional group of bearing materials that might he considered, namely, composites. A brief explanation of the material classifications and their representative characteristics is given here:

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- *Metals.* Metallic materials are normally combinations of metallic elements. They have large numbers of nonlocalized electrons; that is, these electrons are not bound to particular atoms. Metals are extremely good conductors of electricity and heat and are not transparent to visible light; a polished metal surface has a lustrous appearance. Furthermore, metals are quite strong yet deformable.

- *Ceramics.* Ceramics are compounds of metallic and nonmetallic elements; they are most frequently oxides, nitrides, and carbides. The wide range of materials that fall within this classification includes ceramics that are composed of clay, cement, and glass. These materials are typically insulative to the passage of electricity and heat and are more resistant to high temperatures and harsh environments than metals and polymers. With regard to mechanical behavior, ceramics are hard but very brittle.

- *Polymers.* Polymers include plastic and rubber materials. Many polymers are organic compounds that are chemically based on carbon, hydrogen, and other nonmetallic elements. Furthermore, they have very large molecular structures. These materials typically have low density and may be extremely flexible.

- *Composites.* Composite materials include more than one material type. Fiberglass is an example, in which glass fibers are embedded within a polymeric material. A composite is designed to display a combination of the best characteristics of each of the component materials. Fiberglass acquires strength from glass and flexibility from the polymer.

Composites are beyond the scope of this book, but the properties of the other three main classifications of materials will be considered along with a number of materials within each classification.

5.7.1 Density

As pointed out in Sec. 4.12, the density ρ of a solid material is the mass divided by the volume and hence has metric units of kilograms per cubic meter. Typical values lie between 10^3 and 10^4 kg/m^3. Figure 5.4 illustrates the density ordering of various metals, polymers, and ceramics, and Table 5.8 gives quantitative density at room temperature (20°C).

Alloying changes the density only slightly. To a first approximation, the density of an alloy (metallic solid resulting from dissolving two or more molten metals in each other) is given by the "rule of mixtures" (i.e., by a linear interpolation between the densities of the alloy components).

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Table 5.8: Densities of various metals, polymers, and ceramics at room temperature (20°C; 68°F) [*From ESDU (1984).*]

Material	Density, ρ	
	kg/m^3	lbm/in^3
Metals:		
Aluminum and its alloys[a]	2.7×10^3	0.097
Aluminum tin	3.1×10^3	0.11
Babbitt, lead-based white metal	10.1×10^3	0.36
Babbitt, tin-based white metal	7.4×10^3	0.27
Brasses	8.6×10^3	0.31
Bronze, aluminum	7.5×10^3	0.27
Bronze, leaded	8.9×10^3	0.32
Bronze, phosphor (cast)[b]	8.7×10^3	0.31
Bronze, porous	6.4×10^3	0.23
Copper	8.9×10^3	0.32
Copper lead	9.5×10^3	0.34
Iron, cast	7.4×10^3	0.27
Iron, porous	6.1×10^3	0.22
Iron, wrought	7.8×10^3	0.28
Magnesium alloys	1.8×10^3	0.065
Steels[c]	7.8×10^3	0.28
Zinc alloys	6.7×10^3	0.24
Polymers:		
Acetal (polyformaldehyde)	1.4×10^3	0.051
Nylons (polyamides)	1.14×10^3	0.041
Polyethylene, high quality	0.95×10^3	0.034
Phenol, formaldehyde	1.3×10^3	0.047
Rubber, natural[d]	1.0×10^3	0.036
Rubber, silicone	1.8×10^3	0.065
Ceramics:		
Alumina (Al_2O_3)	3.9×10^3	0.14
Graphite, high strength	1.7×10^3	0.061
Silicon carbide (SiC)	2.9×10^3	0.10
Silicon nitride (Si_3N_4)	3.2×10^3	0.12

[a] Structural alloys.
[b] Bar stock typically 8.8×10^3 kg/m^3 (0.30 $lbm/in.^3$).
[c] Excluding "refractory" steels.
[d] "Mechanical" rubber

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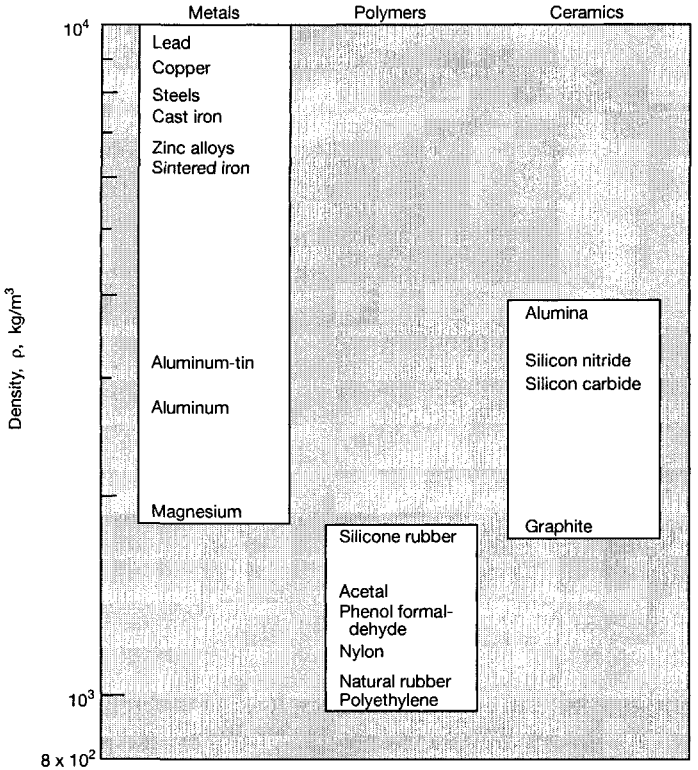

Figure 5.4: Illustration of density for various metals, polymers, and ceramics at room temperature (20°C; 68°F). [*From ESDU (1984).*]

5.7.2 Modulus of Elasticity and Poisson's Ratio

A simple tensile load applied to a bar produces a stress σ_1 and a strain ϵ_1, where

$$\sigma_1 = \frac{\text{load}}{\text{cross-sectional area}} = \text{stress in axial direction}$$

$$\epsilon_1 = \frac{\text{change in length}}{\text{original length}} = \text{strain in axial direction}$$

The elastic constant, or modulus of elasticity (sometimes referred to as "Young's modulus"), can be written as

$$E = \frac{\sigma_1}{\epsilon_1} \tag{5.1}$$

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Although no stress acts transversely to the axial direction, there will nevertheless be dimensional changes in the transverse direction, for as a bar extends axially it contracts transversely. The transverse strains ϵ_2 are related to the axial strains by Poisson's ratio ν such that

$$\epsilon_2 = -\nu\epsilon_1 \tag{5.2}$$

where the negative sign simply means that the transverse deformation will be in the opposite sense to the axial deformation. The metric unit of modulus of elasticity is newton per square meter, or pascal, and Poisson's ratio is dimensionless.

Figure 5.5 illustrates values of the modulus of elasticity for various metals, polymers, and ceramics at room temperature (20°C). The moduli of elasticity for metals and ceramics are quite similar, but those for the polymers are considerably lower. Tables 5.9 and 5.10 give quantitative values of the modulus of elasticity and Poisson's ratio, respectively, for various metals, polymers, and ceramics at room temperature.

5.7.3 Linear Thermal Expansion Coefficient

Different materials expand at different rates when heated. A solid object increases in length by a certain fraction for each degree rise in temperature. This result is accurate over a fairly large range of temperatures. It can be used for calculating how much an object will expand for a given change in temperature, once the extent of the material's expansion is measured. This value is given for each material by a number called "linear expansivity" or "linear thermal expansion coefficient" $\bar{a}$. The metric unit of $\bar{a}$ is Kelvin^{-1}.

Figure 5.6 illustrates the linear thermal expansion coefficient for various metals, polymers, and ceramics applied over the temperature range 20 to 200°C. The polymers have the highest value, followed by the metals and then the ceramics. Table 5.11 gives quantitative values of the linear thermal expansion coefficient for various metals, polymers, and ceramics from 20 to 200°C.

5.7.4 Thermal Conductivity

When two bodies at different temperatures are brought together, the faster-moving molecules of the warmer body collide with the slower-moving molecules of the cooler body and transfer some of their motion to the latter. The warmer object loses energy (drops in temperature) while the cooler one gains energy (rises in temperature). The transfer process stops when the two bodies reach the same temperature. This transfer of molecular motion through a material is called "heat conduction." Materials differ in how fast they let this transfer go on. The metric units of thermal conductivity K_f are watts per meter-Kelvin.

Figure 5.7 illustrates the thermal conductivity of various metals, polymers, and ceramics. The metals and ceramics in general are good conductors, and the polymers are good insulators. Table 5.12 quantifies the thermal conductivity

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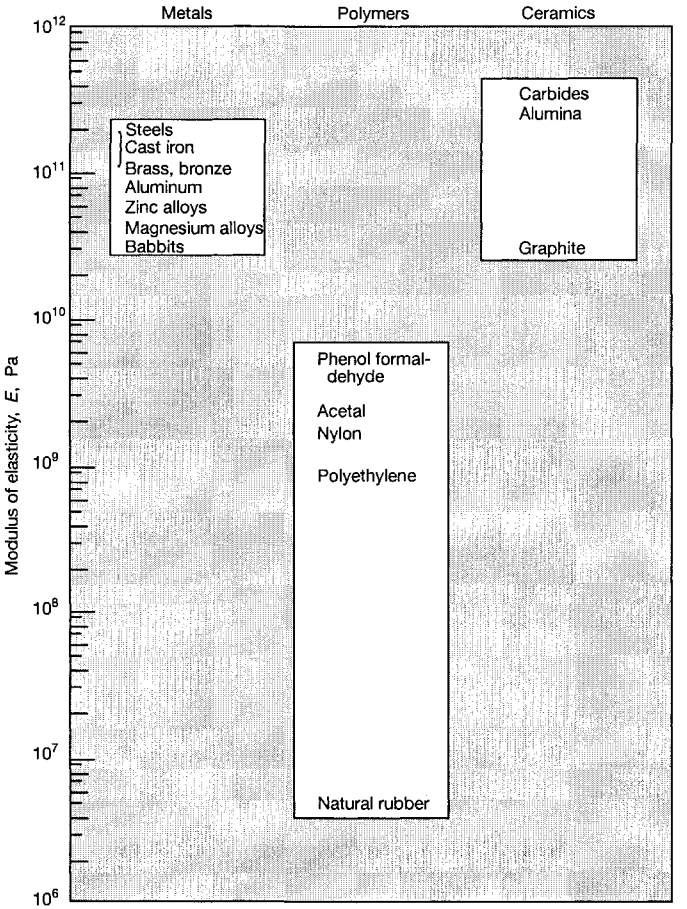

Figure 5.5: Illustration of modulus of elasticity for various metals, polymers, and ceramics at room temperature (20°C; 68°F). [*From ESDU (1984).*]

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Table 5.9: Modulus of elasticity for various metals, polymers, and ceramics at room temperature (20°C; 68°F) [*From ESDU (1984).*]

Material	Modulus of elasticity, E	
	GPa	Mlbf/in.^{2}
Metals		
Aluminum	62	9.0
Aluminum alloys[a]	70	10.2
Aluminum tin	63	9.1
Babbitt, lead-base white metal	29	4.2
Babbitt, tin-base white metal	52	7.5
Brasses	100	14.5
Bronze, aluminum	117	17.0
Bronze, leaded	97	14.1
Bronze, phosphor	110	16.0
Bronze, porous	60	8.7
Copper	124	18.0
Iron, gray cast	109	15.8
Iron, malleable cast	170	24.7
Iron, spheroidal graphite[b]	159	23.1
Iron, porous	80	11.6
Iron, wrought	170	24.7
Magnesium alloys	41	5.9
Steel, low alloys	196	28.4
Steel, medium and high alloys	200	29.0
Steel, stainless[c]	193	28.0
Steel, high speed	212	30.7
Zinc alloys[d]	50	7.3
Polymers		
Acetal (polyformaldehyde)	2.7	0.39
Nylons (polyamides)	1.9	0.28
Polyethylene, high density	0.9	0.13
Phenol formaldehyde[e]	7.0	1.02
Rubber, natural[f]	0.004	0.0006
Ceramics		
Alumina (Al_2O_3)	390	56.6
Graphite	27	3.9
Cemented carbides	450	65.3
Silicon carbide (SiC)	450	65.3
Silicon nitride (Si_3N_4)	314	45.5

[a] Structural alloys.
[b] For bearings.
[c] Precipitation-hardened alloys up to 211 GPa (30 lbf/in.^{2}).
[d] Some alloys up to 96 GPa (14 lbf/in.^{2}).
[e] Filled.
[f] 25-Percent-carbon-black "mechanical" rubber.

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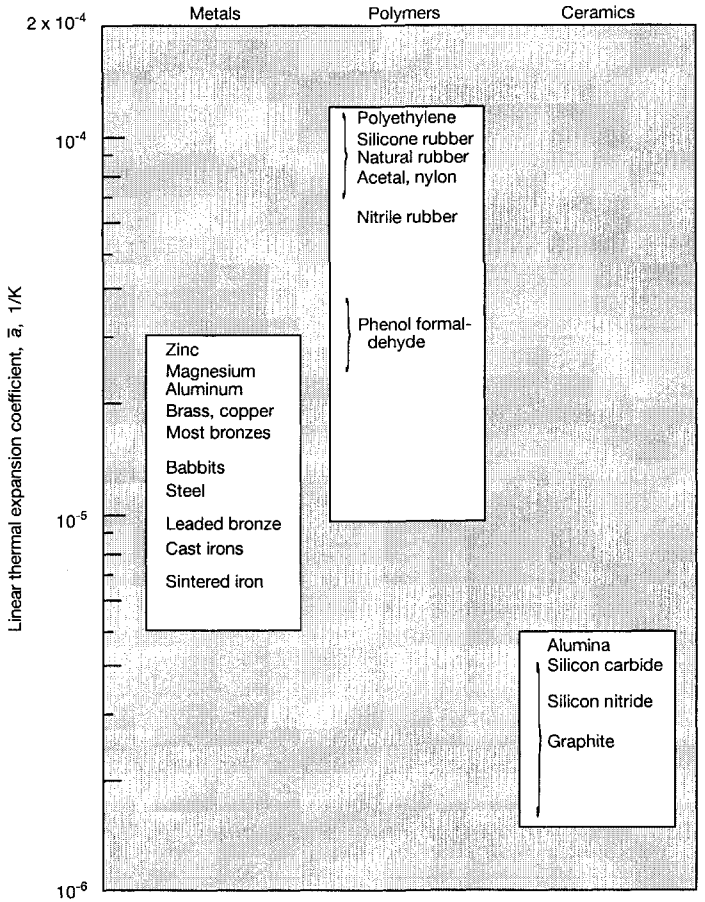

Figure 5.6: Illustration of thermal expansion coefficient for various metals, polymers, and ceramics applied over temperature range 20 to 200°C (68 to 392°F). [*From ESDU (1984).*]

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Table 5.10: Poisson's ratio for various metals, polymers, and ceramics at room temperature (20°C; 68°F) [*From ESDU (1984).*]

Material	Poisson's ratio, ν
Metals:	
Aluminum and its alloys	0.33
Aluminum tin	—
Babbitt, lead-base white metal	—
Babbitt, tin-base white metal	—
Brasses	0.33
Bronze	0.33
Bronze, porous	0.22
Copper	0.33
Iron, cast	0.26
Iron, porous	0.20
Iron, wrought	0.30
Magnesium alloys	0.33
Steels	0.30
Zinc alloys[d]	0.27
Polymers:	
Acetal (polyformaldehyde)	—
Nylons (polyamides)	0.40
Polyethylene, high density	0.35
Phenol formaldehyde[e]	—
Rubber	0.50
Ceramics:	
Alumina (Al_2O_3)	0.28
Graphite, high strength	—
Cemented carbides	0.19
Silicon carbide (SiC)	0.19
Silicon nitride (Si_3N_4)	0.26

[a] Structural alloys.

results given in Fig. 5.7. In Fig. 5.7 and Table 5.12, unless otherwise stated, the temperature is assumed to be room temperature (20°C; 68°F).

5.7.5 Specific Heat Capacity

The nature of a material determines the amount of heat transferred to or from a body when its temperature changes by a given amount. Imagine an experiment in which you take a cast iron ball and a babbitt (lead-based white metal) ball of the same size, heat them both to the temperature of boiling water, and then lay them on a block of wax. You would find that the cast iron ball melts a considerable amount of wax but the babbitt ball, in spite of its greater mass, melts hardly any. It therefore would seem that different materials, in cooling through the same temperature range, give up different amounts of heat.

The quantity of heat energy given up or taken on when a body changes its

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Table 5.11: Linear thermal expansion coefficient for various metals, polymers and ceramics applied over temperature range 20 to 200° (68 to 392°) [*From ESDU* (1984)]

Material	Linear thermal expansion coefficient, $\bar{\alpha}$	
	μm/m·K	μin./in.·°F
Metals:		
Aluminum	23	12.8
Aluminum alloys[a]	24	13.3
Aluminum tin	24	13.3
Babbitt, lead-based white metal	20	11
Babbitt, tin-based white metal	23	13
Brasses	19	10.6
Bronzes	18	10.0
Copper	18	10.0
Copper lead	18	10.0
Iron, cast	11	6.1
Iron, porous	12	6.7
Iron, wrought	12	6.7
Magnesium alloys	27	15
Steel, alloy[b]	11	6.1
Steel, stainless	17	9.5
Steel, high speed	11	6.1
Zinc alloys	27	15
Polymers:		
Thermoplastics[c]	60–100	35–56
Thermosets[d]	10–80	6–44
Acetal (polyformaldehyde)	90	50
Nylons (polyamides)	100	56
Polyethylene, high density	126	70
Phenol formaldehyde[e]	25–40	14–22
Rubber, natural[f]	80–120	44–67
Rubber, nitrile[g]	34	62
Rubber, silicone	57	103
Ceramics:		
Alumina (Al_2O_3)[h]	5.0	2.8
Graphite, high strength	4.5	0.8–2.2
Silicon carbide (SiC)	4.3	2.4
Silicon nitride (Si_3N_4)	3.2	1.8

[a] Structural alloys.
[b] Cast alloys can be up to 15μm/m·K.
[c] Typical bearing materials.
[d] 25 μm/m·K to 80 μm/m·K when reinforced.
[e] Mineral filled.
[f] Fillers can reduce coefficients.
[g] Varies with composition.
[h] 0 to 200°C.

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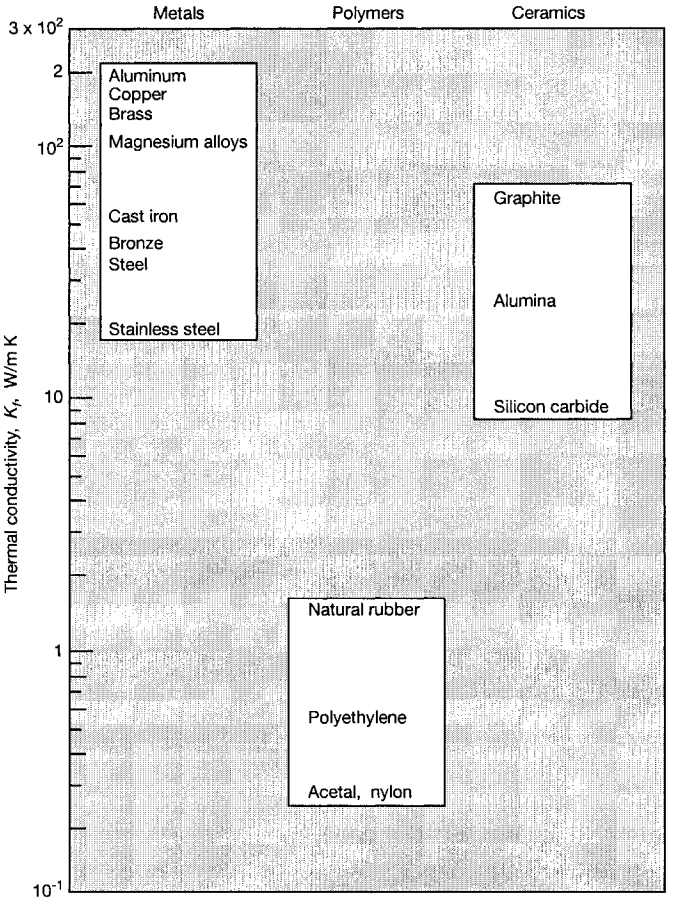

Figure 5.7: Illustration of thermal conductivity for various metals, polymers, and ceramics. [*From ESDU (1984).*]

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Table 5.12: Thermal conductivity for various metals, polymers, and ceramics

Material	Thermal conductivity	
	W/m K	Btu/ft hr °F
Metals:		
Aluminum	209	120
Aluminum alloys, casting[a]	146	84
Aluminum alloys, silicon[b]	170	98
Aluminum alloys, wrought[c]	151	87
Aluminum tin	180	100
Babbitt, lead-based white metal	24	14
Babbitt, tin-based white metal	56	32
Brasses[a]	120	69
Bronze, aluminum[a]	50	29
Bronze, leaded	47	27
Bronze, phosphor (cast)[d]	50	29
Bronze, porous	30	17
Copper[e]	170	98
Copper lead	30	17
Iron, gray cast	50	29
Iron, spheroidal graphite	30	17
Iron, porous	28	16
Iron, wrought	70	40
Magnesium alloys	110	64
Steel, low alloy[c]	35	20
Steel, medium alloy	30	17
Steel, stainless[f]	15	8.7
Zinc alloys	110	64
Polymers:		
Acetal (polyformaldehyde)	0.24	0.14
Nylons (polyamides)	0.25	0.14
Polyethylene, high density	0.5	0.29
Rubber, natural	1.6	0.92
Ceramics:		
Alumina (Al_2O_3)[g]	25	14
Graphite, high strength	125	72
Silicon carbide (SiC)	15	8.6

[a] At 100°C.
[b] At 100°C (~150 W/m· K at 25°C.)
[c] 20 to 100°C.
[d] Bar stock typically 69 W/m K.
[e] Typically 22 W/m·K at 200°C.
[f] Typically 12 W/m· K at 400°C.

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Table 5.13: Specific heat capacity for various metals, polymers and ceramics at room temperature (20°; 68 °F) [*From ESDU (1984).*]

Material	Specific heat capacity, C_p	
	kJ/kg K	Btu/lb °F
Metals:		
Aluminum and its alloys	0.9	0.22
Aluminum tin	0.96	0.23
Babbitt, lead-based white metal	0.15	0.036
Babbitt, tin-based white metal	0.21	0.05
Brasses	0.39	0.093
Bronzes,	0.38	0.091
Copper[a]	0.38	0.091
Copper lead	0.32	0.076
Iron, cast	0.42	0.10
Iron, porous	0.46	0.11
Iron, wrought	0.46	0.11
Magnesium alloys	1.0	0.24
Steels[b]	0.45	0.11
Zinc alloys	0.4	0.096
Polymers:		
Thermoplastics	1.4	0.33
Rubber, natural	2.0	0.48
Ceramics:		
Graphite	0.8	0.2
Cemented carbides	0.7	0.17

[a]Aluminum bronzes up to 0.48 kJ/kg K (0.12 Btu/lb °F).
[b]Rising to 0.55 kJ/kg K (0.13 Btu/lb °F) at 200°C (392°F).

temperature is proportional to the mass of the object, to the amount that its temperature changes, and to a characteristic number called the "specific heat capacity" of the material the body is made from.

$$\therefore \hat{Q} = C_p m_a \left(\Delta t_m\right) \tag{5.3}$$

where

$\hat{Q}$ = quantity of heat, J
C_p = specific heat of material, J/(kg·K)
m_a = mass of body, kg
Δt_m = temperature change, K

Figure 5.8 illustrates the specific heat capacity of various metals, polymers, and ceramics at room temperature (20°C). Polymers have considerably higher specific heat than metals or ceramics. Table 5.13 quantifies the information presented in Fig. 5.8.

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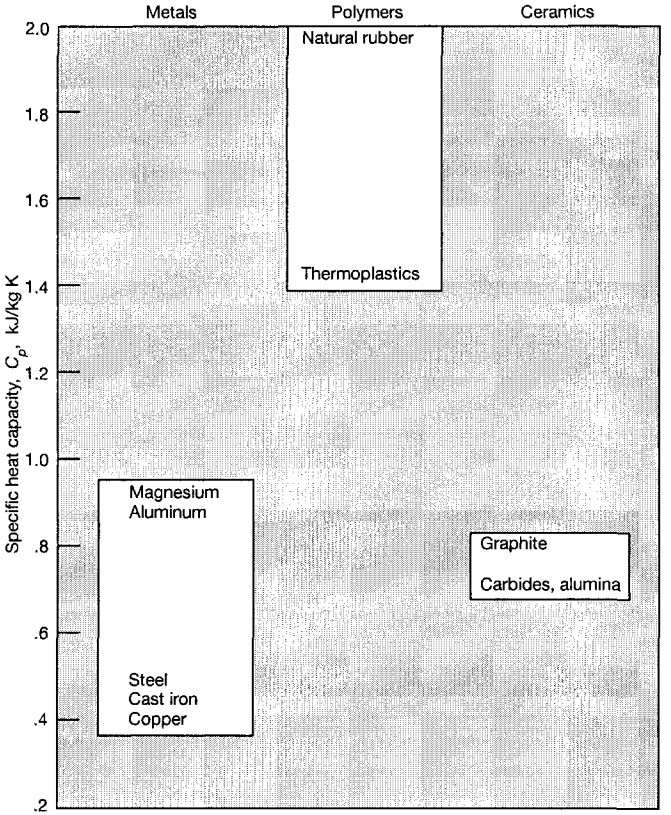

Figure 5.8: Illustration of specific heat capacity for various metals, polymers, and ceramics at room temperature (20°C; 68°F). [*From ESDU (1984).*]

5.8 Closure

In this chapter the general characteristics of bearing materials have been established and discussed. Some desirable characteristics covered in this chapter are compatibility with rubbing counterface materials; embeddability for dirt particles and wear debris; conformability to enable the bearing to accommodate misalignment, geometrical errors, and deflections in structure, strength, corrosion resistance, and fatigue resistance. The various types of bearing material that are now available have been evaluated in terms of these characteristics. These materials consist of metallics (babbitts, bronzes, aluminum alloys, porous metals, and metal overlays such as silver and indium) or nonmetallics (plastics, rubber, carbon-graphite, ceramics, cemented carbides, and metal ox-

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ides). Bearing materials applicable to conformal surfaces, where hydrodynamic lubrication occurs, as well as to nonconformal surfaces, where elastohydrodynamic lubrication occurs, were discussed. The stresses acting on conformal and nonconformal surfaces differ considerably, and therefore the solid surface requirements are quite different. The last section listed representative values of a number of solid material properties required in evaluating fluid film bearings. These properties included density, modulus of elasticity, Poisson's ratio, linear thermal expansion coefficient, thermal conductivity, and specific heat capacity. Values of these parameters were given for a variety of metals, polymers, and ceramics at room temperature. The material developed in this chapter should prove useful in subsequent chapters.

5.9 Problem

5.1 Describe and compare the main types of materials that are available for use as a plain journal bearing when an oil or a grease is undesirable as a lubricant.

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